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ART. IV.—*Superficial Sand Deposits between Brighton and Frankston, Victoria.*

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Abstract.

Four types of sand formations are described: (1) Longitudinal dune ridges which occur with great regularity in the Brighton area; (2) irregular barchan dunes in the Frankston area; (3) coastal ridges in the low-lying area between Mordialloc and Frankston; (4) lunette ridges believed to have been formed on the northern sides of swamps between Brighton and Frankston.

The mode of formation of the deposits is deduced from their shape, orientation and extent, and the stratification and degree of sorting of the sand, while the heavy minerals present and the roundness of grains give an indication of the origin of the sand. Factors which have influenced the physiography of the area are: tectonic movements, forming the low-lying area now occupied by the swamp; climatic changes, leading to formation of dunes and their later preservation by vegetation; and changes in sea level, which have caused the formation of three successive coastal ridges, two of which are very close together behind the present coastline, and one further inland forming the boundary between Carrum Swamp and Dandenong Swamp.

Introduction.

The present investigation has been carried out in an attempt to elucidate the nature and origin of the various types of superficial sand ridges that occur between Brighton and Frankston. The sand ridges in the Brighton district were mapped from aerial photographs which covered the area as far east as Edithvale Road. The position of ridges and depressions could be determined reasonably accurately with the aid of a stereoscope, and most of the ridges were then examined in the field. In the areas not covered by aerial photographs, the boundaries between sand ridges and alluvial flats were mapped on the ground. There is a marked difference in the vegetation cover of the sand ridges and the alluvial flats, which is most noticeable in the south-eastern part of the area, where settlement has not been so close as further north. Here most of the sandy areas have been left uncleared, whereas the alluvial flats are used extensively for agriculture. The most striking feature of the natural vegetation is the presence of bracken on any low sandy area, which may otherwise be almost indistinguishable from the alluvial flats, on which bracken is never found.

Physiography.

On physiographic grounds, the area described is divisible into north-west, central and south-east sectors.

The North-Western Sector.

This includes the coastal plain of the Brighton district, which extends inland for 4-5 miles towards the low foothills of the Eastern Highlands along the Gippsland-road. In the south, it terminates along the northern edge of the low-lying swampy areas which comprise the central sector (see below). Between Brighton and Mordialloc, there is a regular series of long, low, parallel sand ridges with intervening swampy depressions, all of which have a north-westerly trend. They have been described by Hart (1913), who suggested that the formation of regular, parallel valleys was due to "lines of easy erosion" in the Tertiary rocks over which the present drainage system developed.

The ridges, however, have not been previously studied in detail. Hills (1940A) states that "sand ridges were formed on some of the sandy coastal plains, as for instance in the Moorabbin-Highett district" during periods of relative aridity in recent times, but the extent and remarkable regularity of the ridges and shallow depressions, which may be seen on the map (fig. 1) have not been generally realized.

Owing to their parallelism to the present coast, it might be suggested that the ridges are old beach ridges left behind during a retreat of the sea. No shells, waterworn pebbles or other evidence suggestive of beach deposits, however, have been found in association with these ridges, and it is considered, on evidence that will be discussed below, that they are of aeolian origin.

The sand ridges are symmetrical in cross-section and have relatively flat tops. Because of their age, however, any minor morphological details such as a sharp crest, or slight variations in the slopes on either side that might once have existed, may have been modified by erosion. In their straightness and regular parallel arrangement they resemble longitudinal dune ridges, such as have been described by Madigan in Central Australia (1936), and, although the Brighton ridges are broader and much closer together than the Central Australian ones, it seems probable that they were formed under similar conditions and are actually longitudinal dunes. Further to the east on the other side of the low divide referred to as the Cheltenham Axis by Hart (1913), the ridges become shorter and less regular, although the same north-westerly trend of the country is still apparent. The drainage here is in a south-easterly direction towards Carrum Swamp.

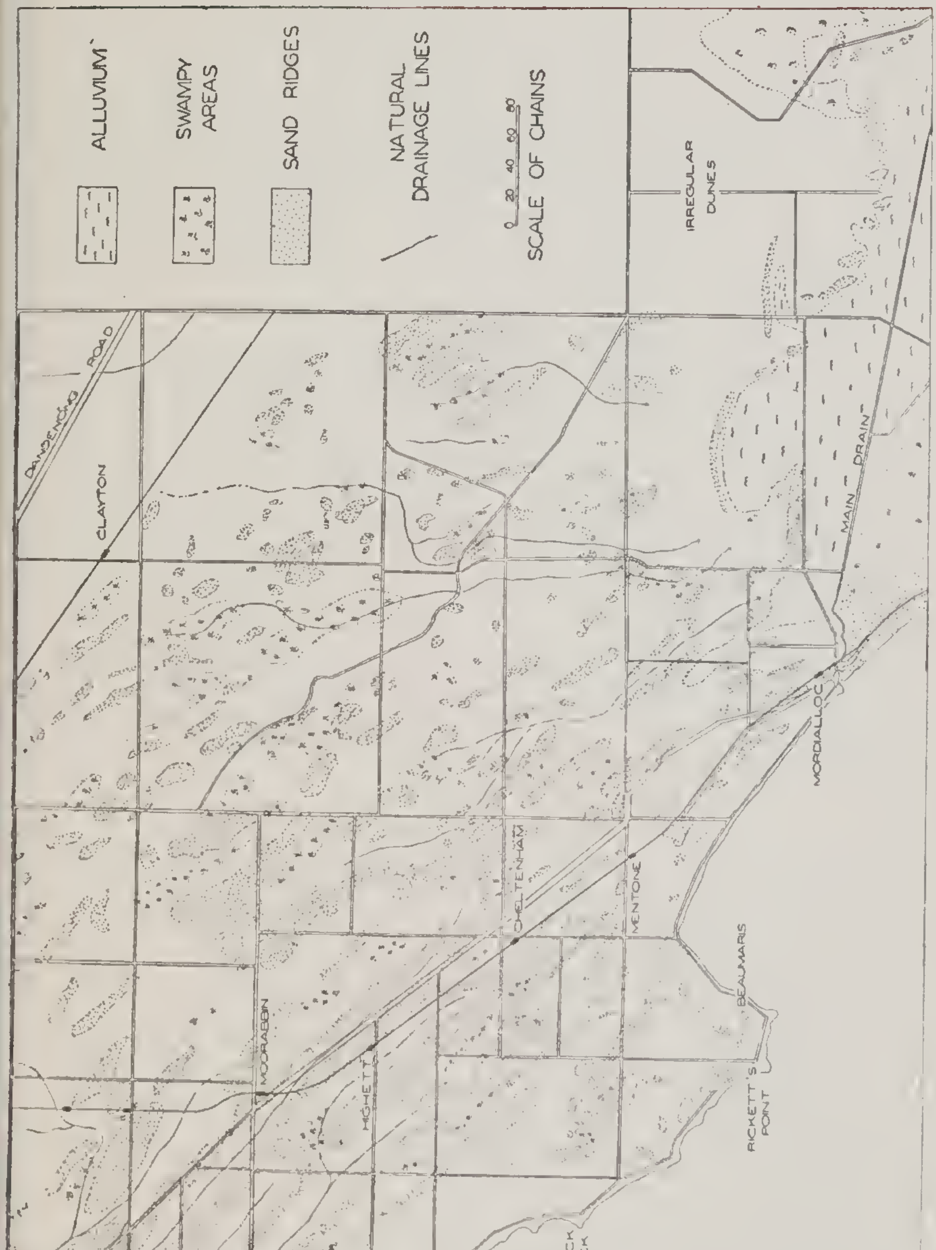

Fig. 1.—Map of Sand Ridges on the Coastal Plain between Brighton and Mordialloc.

South-Eastern Sector.

This part of the area includes the country between Frankston, Carrum Downs and Cranbourne, over which extensive sand deposits are also found. In this sector, the land is higher and not as flat as in the Brighton district, and there is a marked difference in the external form of the sand ridges compared with those in the north-western sector.

Instead of the parallel ridges and valleys found in the north-west, individual sand hills are irregularly dispersed and do not cover the whole of the area. These sand hills are so crowded together and are so irregular in height and size, that their true form is hard to distinguish. They resemble barchans in that most of them are slightly curved and have a steeper face on the concave side, and will be referred to as such in this discussion. At the bottom of the steeper slopes, swampy areas, in which the vegetation is very thick in contrast with the heathy type of vegetation growing on the sand hills themselves, commonly occur.

The depth of sand in these deposits is much greater than in the longitudinal ridges in the north-west, 80-90 feet of sand being exposed in many of the pits along the Frankston-Cranbourne road.

Central Sector.

Between the above two sectors in which sand formations are widespread, is the flat and relatively low-lying area occupied by the Carrum and Dandenong Swamps. Carrum Swamp is separated from the sea by a continuous line of sand ridges parallel to and just behind the present coastline. Further inland, about 1½ miles from the coast at its greatest distance, a similar curved sand ridge forms the boundary between Carrum Swamp and Dandenong Swamp (see fig. 2). This ridge, along which Wells'-road runs, is more or less continuous from Mordialloc to Frankston, and has been referred to as Wells'-road Ridge (Hills, 1940B). The whole of the flat low-lying area extending inland from Wells'-road for about 5 miles will be referred to as the Dandenong Swamp.

Coastal Ridges.—Along the sweeping curve of the coastline between Mordialloc and Frankston, there are no cliffs such as are found to the north and south, the coast being composed entirely of sand. About 3 chains inland is a continuous ridge of sand of fairly uniform height, along which the Melbourne-Frankston railway line has been constructed. Between Mordialloc and Carrum there is only a single main ridge, behind which is a low sandy area descending towards the edge of Carrum Swamp. This ridge becomes wider towards Carrum and splits up into two parallel ridges, between which Kananook Creek flows until it breaks through to the sea at Frankston. A diagrammatic cross-section through this part of the coast is shown in fig. 4.

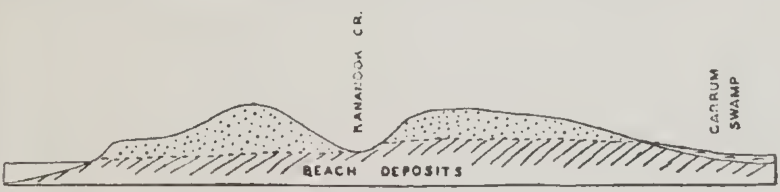

FIG. 4.—Diagrammatic Section through the Coastal Ridges at Seaford. (Not drawn to scale.)

As will be seen in the discussion of their lithology, these ridges are composed of wind-blown sand resting on beach deposits, and they are, therefore, " dune ridges " as defined by Johnson (1919).

Wells'-road Ridge.—This ridge is not as high nor as continuous as the one close to the beach, but it can be followed with some gaps in a curved line from the corner of Edithvale-road and Wells'-road until it joins the coastal ridges just north of Frankston. In most parts where the ridge is very prominent, its south-eastern or seaward edge is more regular and better defined than the landward edge.

Alluvial Flats.—The Carrum Swamp, between Wells'-road and the coastal ridges, has already been described (Hills, 1940B). Although part of it is now permanently under water near Seaford, the general level of the surface, before sinking took place on cultivation, has been stated to have been $4\frac{1}{2}$ feet above sea level.

The Dandenong Swamp is higher than Carrum Swamp, but just as flat. All the water entering the area from the Dandenong and Eumemmerring Creeks is now confined to drains, and the area is no longer swampy. The two most important drains are the Main Drain, which supplies Mordialloc Creek, and a secondary drain which enters the sea through an artificial cut in the coastal sand ridges at Carrum.

Sand ridges form the boundaries of Dandenong Swamp in the north and the south-east (fig. 2), but towards the north-east, the land gradually rises to where Tertiary rocks outcrop at the surface in the neighbourhood of Lyndhurst. The country here becomes undulating, and the Tertiary rocks are in places covered by wind-blown sand.

The south-eastern boundary of the alluvial flats runs approximately north-east from Frankston along the main Frankston-Dandenong road as far as Carrum Downs, and then continues east towards Cranbourne. Thus, for part of the way, it follows a north-easterly extension of Selwyn's Fault (Hills, 1940A, p. 160). Along the edge of the swamp, the sand hills are very low and irregular, but they increase in height fairly rapidly away from the alluvial flats, not so much because of increasing height

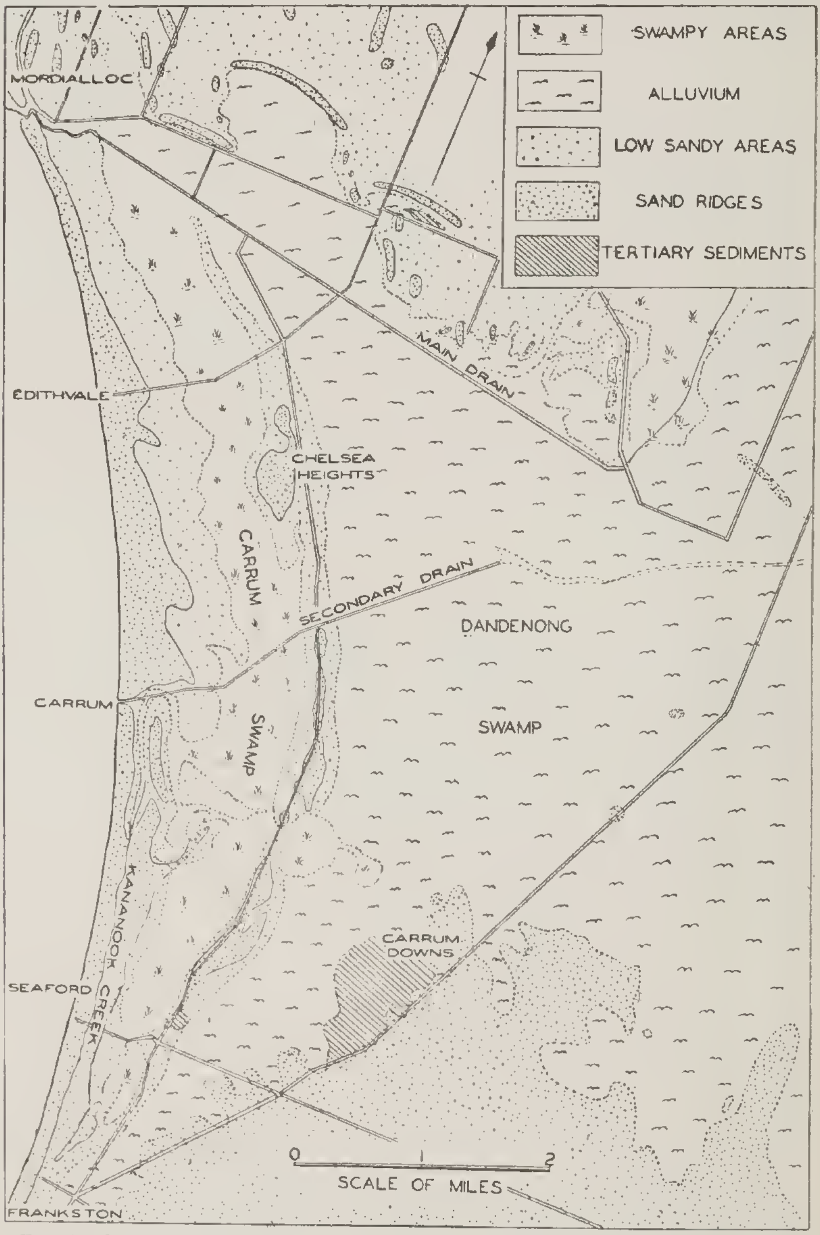

Fig. 2.—Map showing Areas of Sand Ridges and Alluvium between Mordialloc and Frankston.

of sand, but because of the increasing height of the underlying surface of Tertiary and Silurian rocks, which are exposed in many parts of the Frankston district.

Along the northern boundary of Dandenong Swamp, just east of Mordialloc, there are two types of boundary ridges. On the northern side of the Main Drain and east of Edithvale-road are low, irregular, sand ridges, many of which are entirely surrounded by alluvium, and which are probably related to the less regular sand dunes of the north-western sector. The relationship between these sand ridges and the alluvium can be seen in a pit in a low sand ridge near the Edithvale-road. This pit has been continued to a depth level with the surface of the surrounding alluvium, and no change in the nature of the sand can be seen. Below this depth the sand is continuous, indicating that the sand ridge has been partly buried around its base by alluvium. Unlike the south-eastern boundary of the alluvial flats, where the land rises fairly suddenly, the land behind these boundary ridges near the Main Drain rises only gradually towards the north and north-west.

The other ridges along this boundary of the swamp can be seen on the map (fig. 2) mainly between Mordialloc and Edithvale-road, and do not seem to be related to any of the sand ridges already described. They are of uniform height for practically the whole of their length. They trend almost due east and west, are slightly curved with the concave side facing south, and are much longer than any of the other ridges in this part of the area (see fig. 2). The most prominent of these ridges can be seen in a section along the Edithvale-road, just north of Governor-road. The width here is approximately 2 chains and the height approximately 10 feet above the alluvial flats. On the northern side, the land is higher and undulating, with Tertiary rocks outcropping at the surface, which is covered in places by the irregular sand ridges referred to in the North-Western Sector. To the east of these three ridges and on the other side of the Dandenong Creek, there is another relatively long ridge, which is similar in form to those just described, but which could not be closely investigated owing to the fact that it is in a proclaimed military area. As far as could be seen from the road which crosses this ridge, it continues for some distance in an ESE. direction (fig. 2), and both to the north and south of it the land is very flat.

The origin of these ridges is not clear. In their length, uniform height and curvature, they resemble the coastal ridges, and from a consideration of their position it might be suggested that they are remnants of yet another coastline behind Wells'-road. There is, however, no evidence to show that the coastline has been further inland than Wells'-road since the elevation of the marine Tertiaries. The south-eastern and part of the northern boundary between alluvial flats and the higher sand ridge areas, along which one would expect to find evidence of such a coastline, is very irregular and follows the base of the sand ridges as can be seen from the map (fig. 2). Also, the unbroken uniform height of each of these three sand ridges suggests that they have not been greatly altered by erosion and are probably younger than Wells'-road ridge. It is therefore improbable that they were formed along a former coastline.

On the other hand, these sand ridges cannot be classed with the longitudinal dune ridges further east because of their different orientation and their curvature, nor with the barchan dunes because of their uniform height and greater length in relation to width. A possible explanation of their formation is that they have been built up on the northern sides of the swamps in much the same way as the lunettes described by Hills (1939). An important difference, however, is that, whereas the lunettes in northern Victoria are composed of fine dust particles, which is the only material available in the areas where they are formed, the ridges marginal to the Dandenong Swamp are composed almost entirely of sand, probably derived from the sand ridges further south, and from the sandy alluvium of the swampy areas.

With the exception of parts of the Frankston and Cranbourne areas, where older rocks occur, most of the area dealt with in this paper is underlain by arenaceous or argillaceous Tertiary sediments.

Lithology.

In order to determine any significant variations in the lithology of sands deposited under different conditions, the following properties of the sand from each type of deposit were investigated.

Mechanical Composition.—The degree of sorting of the sand was studied by passing the sample through a series of wire mesh sieves, the size of each mesh being half that of the one above it. The sizes used were: $\frac{1}{8}$ mm., $\frac{1}{4}$ mm., $\frac{1}{2}$ mm., and 1 mm., and, where necessary, 2 mm. and 4 mm. The percentage weights remaining on each sieve and in the pan were then calculated, and the results of all mechanical analyses compared by means of histograms (fig. 3).

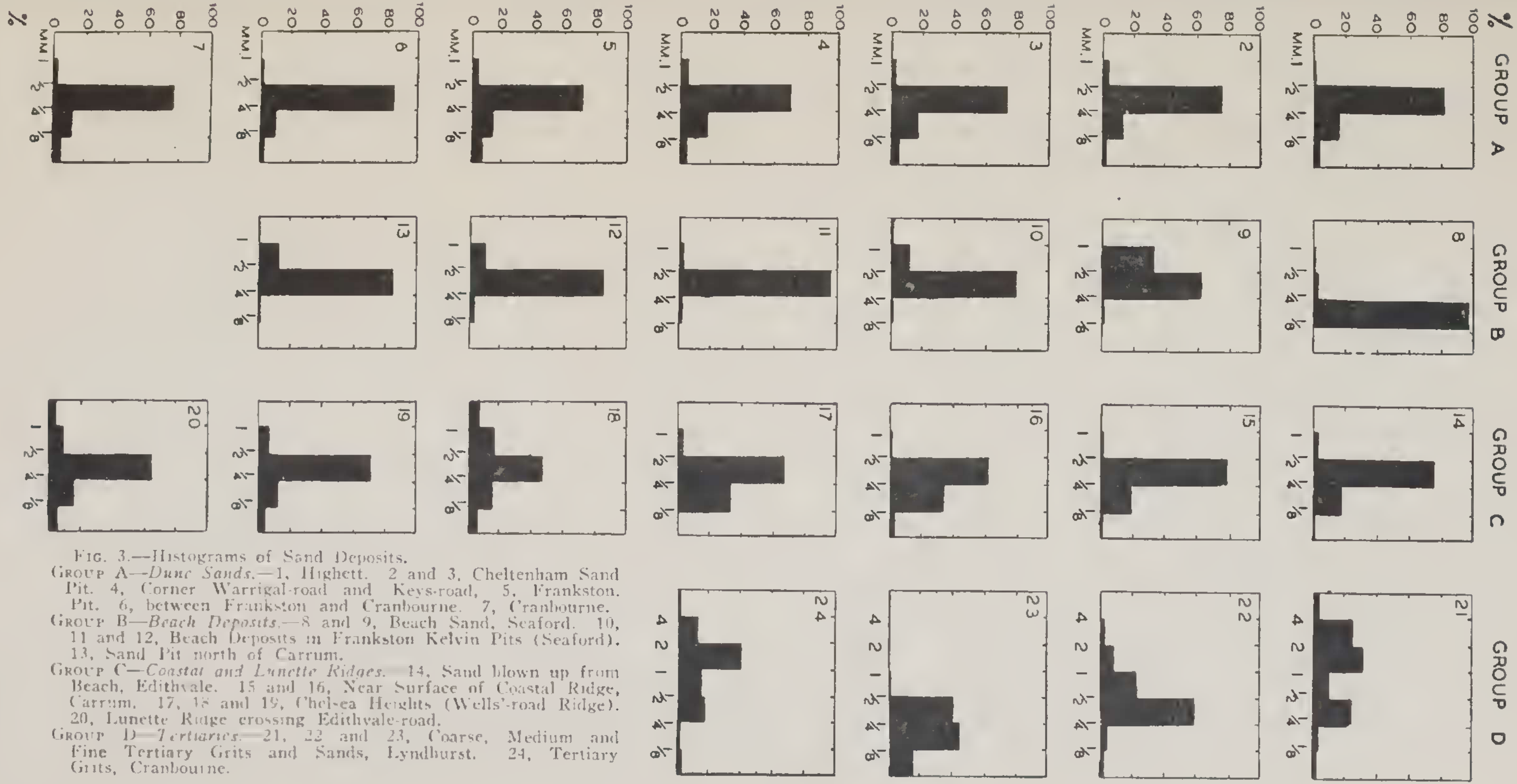

FIG. 3.—Histograms of Sand Deposits.

GROUP A—*Dune Sands.*—1, Highett. 2 and 3, Cheltenham Sand Pit. 4, Corner Warrigal-road and Keys-road. 5, Frankston. Pit. 6, between Frankston and Cranbourne. 7, Cranbourne.

GROUP B—*Beach Deposits.*—8 and 9, Beach Sand, Seaford. 10, 11 and 12, Beach Deposits in Frankston Kelvin Pits (Seaford). 13, Sand Pit north of Carrum.

GROUP C—*Coastal and Lunette Ridges.*—14, Sand blown up from Beach, Edithvale. 15 and 16, Near Surface of Coastal Ridge, Carrum. 17, 18 and 19, Chelsea Heights (Wells'-road Ridge). 20, Lunette Ridge crossing Edithvale-road.

GROUP D—*Tertiaries.*—21, 22 and 23, Coarse, Medium and Fine Tertiary Grits and Sands, Lyndhurst. 24, Tertiary Grits, Cranbourne.

When sampling sand, particularly that of beach deposits, for mechanical analysis, it was found necessary to ensure that all the sand was obtained from the one lamina or bed, as frequently two successive laminae are composed of grains of a different size, this depending largely on the conditions prevailing at the time of their deposition. Although each individual lamina may be well sorted, this fact may be obscured if they are not kept separate.

This precaution was not found to be necessary for dune sands, but in these, as in all the sand deposits, if the sand is to be obtained in the same condition as it was deposited, it must be taken from at least 2 or 3 feet below the surface. This is necessary because the surface sand of the A soil horizon has been leached, being now a pale-grey in colour and containing small amounts of humus. Below this horizon, there is generally a narrow zone of dark-brown sand, partly cemented, and below this again the original sand which is usually slightly iron-stained. The depth to which weathering and soil formation have taken place in sand varies from place to place, being greater on flatter areas such as that just north of Carrum, than on steeper and better-drained slopes as on the sides of the Frankston sand ridges.

Roundness of Grains.—Sand from each grade of the mechanical analysis was examined in reflected light under a binocular microscope, and the degree of rounding of the grains was noted. No quantitative analysis of the roundness of grains was undertaken as it was not felt that such a detailed study would serve any useful purpose in this investigation.

Heavy Minerals.—The heavy mineral assemblages obtained from all sand deposits, as well as from alluvium and Tertiary sediments, were examined and compared (see table of heavy minerals). Separation of the minerals was carried out in bromoform, and for clean sand no preliminary treatment was required. In dealing with samples of material such as alluvium or Tertiary sediments which contain varying amounts of clay, this had first to be removed by washing before a separation in bromoform could be obtained.

Stratification.—Because of the loose, unconsolidated nature of many of the sand deposits, stratification, if present, could not always be seen on a fresh surface unless there was some marked change in the sand in succeeding laminae. Normal dune bedding can be seen, however, on the sides of many of the sand pits which have been exposed to weathering for some time.

Table of Heavy Mineral Assemblages.

	No.	Locality	Andalusite	Augite	Biotite	Brookite	Epidote	Hornblende	Ilmenite	Limonite	Leucoxene	Magnetite	Pyrite	Rutile	Tourmaline	Zircon
Alluvium	1	Carrum Swamp	C		a		r		A	a	r				C	0
	2	Carrum Swamp	r						a	r	r	a	V	C	C	C
	3	Carrum Swamp	r						A			C		C	a	C
	4	Main Drain	V	V	A			a	a	C		C			0	C
	5	Main Drain	r		A			a	r	C		C			r	r
	6	Beach Sand	0		r	V			a	C	r	V		r	a	C
	7	Lunette Ridge	V						a	r		r		r	C	C
Coastal Ridges	8	Seaford	C						C	C		A		r	r	r
	9	Carrum	r		C				a		r	r			C	0
	10	Chelsea Heights	0			V		V	A	0	r			C	C	a
	11	Chelsea Heights	r		V	V	r		a	r	r		V	0	C	C
Dune Sand	12	Highett	r			V			A	r	r	r		0	C	C
	13	Highett	r			V			A		C			C	C	a
	14	Cheltenham	V			r			A		r	a		C	C	a
	15	Cheltenham	0						A			C		0	C	C
	16	Cranbourne	r			V		V	A	C	r	C		C	C	C
	17	Frankston	0			V			A	r	r	C		r	a	a
	18	Between Frankston and Cranbourne	r						A	C	r	V		r	C	0
Tertiary Sands & Grits	19	Lyndhurst (Medium)	V			r			A			V		0	0	0
	20	Lyndhurst (Fine)	r			r			A		r	r		r	0	A
	21	Cranbourne	0				r		A		V	r		0	C	A
	22	Warragul Road					r		A					r	0	0

A - very abundant. C - common r - rare.
a - abundant 0 - occasional. V - very rare.

Lithological Descriptions.

Sand Ridges of the North-Western and South-Eastern Sectors.

On comparing histograms of sand collected from many of the pits in the Cheltenham and Moorabbin districts, and also from between Frankston and Cranbourne, it was found that the results were remarkably consistent. These sands are very well sorted (see histograms 1-7). In all samples, over 60 per cent. and in most cases over 70 per cent. of the whole fell into one grade ($\frac{1}{4}$-$\frac{1}{2}$ mm.), this grade being the "chief ingredient" as defined by Udden (1914). Of the remainder, the percentage of the sample with grains smaller than those of the chief ingredient, i.e., Udden's "finer admixtures," was always found to be greater than that of grains coarser than the chief ingredient. It seems to be generally accepted that sands which have a consistently small range in grain size and a high degree of sorting are found only in aeolian dunes and in beach deposits, but the uniform size of the chief ingredient of the sand ($\frac{1}{4}$-$\frac{1}{2}$ mm.) throughout all these deposits in Cheltenham and Frankston districts is typical only of dune sand (Retgers, 1895). Although each sample of beach sand is well sorted, the predominating grain size varies from one lamina to the next.

On examining sand from each grade in reflected light, it was found that the proportion of rounded and sub-rounded grains present increases with increasing size, most grains greater than 1 mm. diameter being rounded. This rounding refers only to the quartz grains, which constitute over 99 per cent. of the sand in all the samples examined. The small percentage of heavy minerals, which are nearly restricted to the smallest grade ($< \frac{1}{8}$ mm. diameter), are mostly well rounded, with a few prismatic and angular grains, although all the quartz grains of similar size are angular.

Heavy Minerals.—In all sands collected from the pits referred to above, the most abundant heavy minerals are ilmenite, zircon (round and prismatic), tourmaline (rounded and angular), and rutile. Less common are magnetite, andalusite, limonite and leucoxene (associated with ilmenite). Brookite, hornblende and epidote were recorded from some samples, but not more than one or two grains per slide. In the samples in which these last-named minerals were not recorded, it does not necessarily mean that they are absent from that particular deposit, since it is possible that if it had been practicable to obtain a larger representative sample from that locality, these minerals although rare, would have been recorded.

Stratification.—Typical dune bedding with narrow, closely spaced laminae is present in both the longitudinal and barchan sand ridges, and can be seen on weathered surfaces of many of the sand pits. The direction and angle of dip are variable and cross-bedding is common. In all these deposits the grain size is fairly uniform over a considerable vertical range, i.e., there is no change in grain size from one lamina to the next, and consequently stratification cannot usually be detected on a fresh surface. In addition to this stratification, a peculiar type of horizontal bedding can be seen in the upper parts of nearly all sand pits in the longitudinal ridges of the Cheltenham district, and along Warrigal-road. At regular intervals, usually about 3 in. to 5 in., narrow bands of relatively hard sand, approximately 2-3 mm. thick, project out slightly from the side of the pit. The sand in these bands is more iron-stained than the average, and also contains small amounts of clay. It is possible that the hard bands represent successive surface layers, in which the cementing material was deposited before additions of sand were made during the growth of the ridges. The iron-stained clay may have been deposited as red dust during dust storms and accompanying mud rains similar to, but more severe than, those which sometimes occur over the area in summer at the present time.

Coastal Ridges.

The existence of extensive sand pits near Seaford and Carrum made it possible for these deposits to be closely investigated, and from this investigation it has been concluded that the ridges are composed of wind-blown sand and rest on beach deposits which are exposed in the lower parts of the sand pits.

Beach Deposits Underlying the Ridges.—The most striking feature of these deposits in contrast to the aeolian sand ridges, is the presence in them of a large number of waterworn pebbles and many marine shells. The pebbles consist mainly of limonite or ferruginous grits derived from the Tertiary rocks, and of metamorphosed sandstone similar to that in the metamorphic aureole of the Mt. Eliza granite. Several rounded fragments of silicified wood comparable with that which occur beneath the Older Basalt at Oliver's Hill, Frankston, were also found.

A shell bed identical in type with those on the present beach is exposed in the sand pit near Seaford about $\frac{1}{4}$ mile from the sea. The bed, which is about 2 inches thick and 1-2 feet wide, consists almost entirely of entire and broken valves of *Amphidesma* mixed with very coarse, well-sorted sand and abundant flakes of biotite. It extends for about 10 yards in a line parallel to the present coastline. Practically all the shells lie with their convex surfaces uppermost, and it is therefore probable that they were deposited below high-water level. The height of this shell bed above a similar one formed just below high-tide mark on the beach was found to be $3\frac{1}{2}$ feet.

These beach deposits are stratified, and alternate laminae of fine and coarse sand can be seen in many sections through the ridges, particularly along the side of the drain at Carrum, and in the lower 1-2 feet of the shallow pit just north of Carrum, where the sand laminae dip consistently W.S.W. (towards the coastline) at approximately 2°-4°. This pit is not actually in the main sand ridge but in the lower sandy area behind the ridge, and the surface sand is being removed and roughly separated into coarser and finer grades, which are used for building sand and glass making, respectively.

The mechanical composition of sand from some of these laminae is shown in fig. 3, Histograms Nos. 10-13. Neglecting the numerous pebbles present in many samples, the sand was found to be very well sorted with over 80 per cent. in the chief ingredient in most samples. It thus resembles dune sand in the high degree of sorting and the small range in grain size, but there is no record of pebbles ever being found scattered throughout dune sands, and none have been found in the Brighton and Frankston dunes. Another point of difference is that, although the sand from these beach deposits is well sorted, it is not uniform in grain size from bed to bed, that is, instead of the highest percentage of the sample always being found in the grade $\frac{1}{2}$-$\frac{1}{4}$ mm. as in the Cheltenham-Frankston dune sands, the predominating grain size varies in different laminae. For example, in the sand found associated with the shell bed described above, the grade 1-2 mm. forms the chief ingredient, whereas just above this bed the predominating grain size is between $\frac{1}{2}$ and $\frac{1}{4}$ mm.

On examining the histograms of these sands, it can be seen that in most of the samples the percentage of sand coarser than the chief ingredient is slightly higher than that finer than the chief ingredient, and the almost complete absence of grains $< \frac{1}{8}$ mm. in diameter seems to be characteristic. A similar result was obtained for sand collected from the surface of the beach exposed by the retreating tide (Histograms Nos. 8 and 9). Further investigation of sands on the present beach between Mordialloc and Frankston showed that laminae composed of fine sand are, in general, better sorted than those composed of coarse sand, and that very fine or coarse laminae are not as common as those composed of grains between $\frac{1}{4}$ and $\frac{1}{2}$ mm. in diameter. On the beach, the high degree of sorting of the sand can be observed only where the surface has not been disturbed in any way.

The heavy minerals found to be abundant or common in the dune sands are also present in the beach deposits (table of heavy minerals, Nos. 6, 8 and 9). In addition, biotite, which has not been recorded for any of the dune sands other than the coastal dunes, is present in many of the samples from the beach deposits in the sand pits, and from the present beach where it is particularly common at low tide mark. In the light minerals, although quartz is by far the most abundant mineral, shell fragments are also common in sand from the beach, and present, but rare, in sand from the pits.

The Ridges.—In contrast with the beach deposits underlying them, the sand forming the coastal ridges is unstratified and contains no shells or pebbles.

In mechanical composition, this sand is similar to dune sand in that the grade $\frac{1}{4}$-$\frac{1}{2}$ mm. is always the chief ingredient and the percentage of finer admixtures is greater than the percentage of coarser admixtures. The degree of sorting, however, varies and, in some samples taken from near the top of the ridge near Carrum, there is a high percentage of grains in both the $\frac{1}{4}$-$\frac{1}{2}$ mm. and $\frac{1}{8}$-$\frac{1}{4}$ mm. grades (Histogram No. 17). This might be expected if the sand forming the ridges had been blown up from the beach in the immediate vicinity, where laminae composed of grains of varying sizes were present. In travelling over such a short distance, there would be little chance of any sorting of the grains.

The heavy minerals found in this wind-blown sand are the same as those found on the beach sand, but biotite, although present, is not as common as in the beach deposits.

Shell fragments also occur but, like biotite, they are not nearly as abundant as on the beach.

Wells'-road Ridge.—The mechanical composition of sand from near the surface of this ridge varies from place to place. Some of it is not very well sorted (Histogram No. 18). Some resembles dune sand (Histogram No. 19), and some is similar in composition to the sand near the surface of the coastal dune ridge near Carrum (Histogram No. 17).

In the heavy mineral assemblages, biotite, although very rare, has been found in one sample from Chelsea Heights, but not in the others. As well as the common minerals (ilmenite, zircon, tourmaline, rutile, andalusite), brookite, epidote and hornblende have also been identified in these samples; shell fragments and pebbles are absent.

Considering the absence of shells and pebbles, it seems probable that the ridge is composed entirely of wind-blown sand, and was built up just behind a former coastline, from sand blown up from the beach, which was then situated along the south-east side of the ridge.

Alluvium.—The surface soil of both Carrum and Dandenong Swamps is sandy, but contains a fair amount of organic matter and is, therefore, dark in colour. In Carrum Swamp, this surface layer is underlain by sand containing marine fossils, the most common of which is *Arca trapezia*. Behind Wells'-road, no shell layer could be found, although numerous channels were examined. This is in agreement with the supposition that, whereas the Carrum Swamp area has recently been covered by the sea, Dandenong Swamp has not.

Heavy minerals present in alluvium from Carrum Swamp and in silt and sand brought down by Dandenong Creek and deposited in the Main Drain include ilmenite, zircon, tourmaline and andalusite in all samples. Rutile and biotite were also present in some samples from Carrum Swamp. In the alluvium deposited in the Main Drain, the most noticeable feature is the abundance of biotite and hornblende (see table of heavy minerals, Nos. 4 and 5).

Lunette Ridges.—The depth of sand in these ridges is not very great, and in a section which has been cut through one of them, where it crosses Edithvale-road, the sand can be seen resting on a layer of clay and pebbles of limonite, which in turn rests on consolidated Tertiary grits at the same elevation as those exposed at the surface to the north of the ridge.

From what could be seen of the sand forming this ridge, it is unstratified as in typical lunettes. Mechanical analysis showed it to be less well sorted than normal dune sands as it contains several larger grains as well as some clay.

The heavy minerals present are the same as those found in the dune sands.

Tertiary Sediments.—Over the whole of the area from Brighton to Frankston, Tertiary rocks are exposed at the surface, or are present at no great depth beneath the sand and alluvial deposits.

West of the Cheltenham axis, these rocks outcrop along all the valley floors and are exposed beneath the sand in pits and sections through many of the ridges. They vary from pale-coloured clays found along the lower parts of Elsternwick Creek to ferruginous sandstones found towards Cheltenham and Mordialloc. Beneath the sand ridges, the Tertiary rocks are generally found at a higher level than in the adjacent valleys, and consist mainly of loose and partly consolidated grits and sands, in some places very similar to the overlying dune sand except for the large percentage of clay present. These sediments can be seen in sections along the Frankston and Sandringham railway lines, and also in sand pits along Warrigal-road.

On the eastern side of the Cheltenham axis, the Tertiary rocks exposed differ from those described above chiefly in the absence of clays and the presence of unconsolidated grits and abundant limonite concretions.

In the Lyndhurst gravel pit, which is approximately 9 miles north-east of Frankston and 4 miles south-east of Dandenong, very fine unconsolidated sand, in which the grains are all $< \frac{1}{2}$ mm. in size (see Histogram No. 23), is exposed at the bottom of the pit. It is not as well sorted as dune sand and contains a small amount of clay. Horizontal bedding can be seen where the sand has been partly cemented by limonite. Above this fine sand and apparently conformable with it are coarse sands mixed with larger quartz pebbles and clay, all of which are stained intensely red by limonite. Higher up, these sands pass into coarse grits and gravels.

The deposits are roughly stratified, and cross bedding is very common, but there appears to be no consistent direction of dip of the current-bedded layers. The most striking feature of most of these deposits is their intense red colour, due to limonite staining.

Very hard ferruginous grits outcrop approximately 3 miles east of Mordialloc between the main lunette ridge described above and the low sand dunes to the south of it (fig. 2). Over the rest of the Dandenong Swamp, no Tertiary rocks are found at the surface, but where bores or deep channels have been made, ferruginous grits and fine sands have been brought to the surface.

The grits again outcrop near the south-eastern boundary of Dandenong Swamp in the neighbourhood of Carrum Downs, and in this locality concretionary forms of limonite are common on the surface. Material brought up from a well situated about $\frac{1}{4}$ mile from the main Frankston-Dandenong road was found to consist almost entirely of fine white sand similar to that underlying the grits at Lyndhurst and Cranbourne, but without the limonite staining. Grits similar to those at Lyndhurst also outcrop at one point along Wells'-road, just north of Carrum Vale-road (fig. 2).

Results of mechanical analyses of sands and gravels from Lyndhurst and Cranbourne (Histograms Nos. 21-24) show that the coarser material has been very poorly sorted and this, combined with the irregular current bedding, suggests that these sediments have been deposited very rapidly, probably from rivers, and may perhaps be piedmont deposits.

Heavy minerals present in these grits include ilmenite, magnetite, zircon, tourmaline, rutile and andalusite. Rare grains of brookite were recorded in samples from Lyndhurst, and rare epidote from Cranbourne and also a pit on Warrigal-road. The various types of zircon—rounded, prismatic and stumpy—and also the different varieties of tourmaline, ranging from bluish-grey to pink and brown, are similar to the zircon and tourmaline grains present in the overlying sand deposits. Thus, all the heavy minerals found in the Tertiary deposits are also found in the sand ridges and beach deposits, with the addition of biotite in the beach deposits, and biotite and hornblende in the alluvium brought down by the Dandenong Creek.

In the Frankston area, Tertiary grits are exposed in many sections along the Frankston-Cranbourne road. These grits are similar to those found further north and west, but, in addition, they contain abundant large and well-formed flakes of kaolinite. Because of the size of these kaolinite "books," it is probable that the mineral has been formed after the deposition of the grits, in which it occurs, by alteration of felspars originally present.

Where the passage from Tertiary rocks to dune sand is exposed near one of the old Frankston sand pits near the Stony Point railway line, the dune sand can be seen resting on a layer of well-rounded and closely packed pebbles of Tertiary grits, approximately 1 inch in diameter. Below this is normal Tertiary rock. These pebbles may represent "lag gravels" left by the wind prior to the accumulation of sand forming the dunes. A similar layer of rounded pebbles was found overlying the Tertiaries near the corner of North-road and Boundary-road. Although this locality is just outside the area covered by the sand ridges, the gravels are overlain by approximately 3 feet of wind-blown sand drift. In all other sections where the passage from Tertiary rock to dune sand is exposed, no such gravels were found, and their local occurrence probably depends on the nature of the Tertiary sediments at that particular place.

Summary of Lithology.

Mechanical Composition.

As can be seen from the histograms, dune and beach sands can be distinguished from other sediments by the small range in grain size and by the high degree of sorting. However, for differentiating between these two types of sands, a mechanical analysis does not prove very satisfactory if the sand alone is analysed and the presence or absence of pebbles ignored. Three small points of difference have been observed, and the most striking of these is the size of the chief ingredient, i.e., the predominating grain size. As has been pointed out above, in all the dune sands examined, the predominating grain size is between $\frac{1}{2}$ and $\frac{1}{4}$ mm., but in the beach sands it varies from place to place. In one sample, most of the grains are between 1 and $\frac{1}{2}$ mm. in diameter, whereas in another they are between $\frac{1}{4}$ and $\frac{1}{8}$ mm. Secondly, in the dune sand, the percentage of finer admixtures was found to be higher than that of the coarser admixtures, whereas in beach sands the reverse was found to be true. Thirdly, there is an almost complete absence of grains less than $\frac{1}{8}$ mm. in diameter from the beach sands.

As can be seen from the histograms, the range in grain size in the Upper Tertiary sediments is much greater than in the superficial sand deposits, and the degree of sorting is much less. Coarse grit, sands, and clay have apparently all been deposited simultaneously in the one spot, and this, together with the irregular current bedding, seems to exclude the possibility of their having been deposited under marine, esturine, or lacustrine conditions, and, as suggested above, they are probably fluviatile in origin.

Roundness of Grains.—In all the superficial sand deposits, the roundness of grains decreases with decreasing size. This is also true for the smaller grades in the Tertiary sediments, but in these, the larger grains ($>$ 2 mm. in diameter) instead of being more rounded, are more angular than the coarse sand fraction.

As far as could be judged by estimation alone, without any quantitative analysis of degree of rounding, there is no difference between the rounding of grains in beach sand and those in dune sands. In all the samples examined, there appears to be a mixture of very well rounded and angular grains. It does not seem probable that the large number of angular grains present, even in the coarsest grades of dune and beach sand, could be due to recent fracture of older grains, so that it may be suggested that the sand has been derived both from older sedimentary rocks and directly from igneous rocks. It would, therefore, be very difficult to determine the relative amounts of rounding due to wave action along the beach and to wind action during the formation of the dunes, but, because of the short distance over which the dune sand has been transported by the wind, rounding due to this agency was probably very slight. It has been stated by Anderson (1926) that water is more effective in rounding grains than is wind, and that the beach presents the ideal situation for the rounding of sand grains.

Stratification.—As has been pointed out above, the fundamental difference in stratification of dune and beach sands is the uniform grain size of the former, and the variation from one lamina to the next in the latter. Current bedding is common in both types of deposit, and, although the angle of dip of the narrow laminae is variable, it is generally much less in the beach deposits than in the dune sands.

The regular horizontal bedding exposed in the Cheltenham, Warrigal-road and Clayton-road pits described above seems to be peculiar to the upper parts of the longitudinal dunes inasmuch as it has not been observed in any of the pits in the sandhills in the Frankston district.

Heavy Minerals.—The heavy minerals occurring abundantly in the dune sands, beach deposits and dune ridges, namely, ilmenite, zircon, tourmaline, and rutile, and, less commonly, magnetite, andalusite, and leucoxene, are similar to those found in the Tertiary sediments. Brookite, which is rare in all the sand deposits, is also present in the Tertiaries. Limonite, which is present in most of the samples from the recent sand formations, is absent from the Tertiary rocks as actual grains, although it is present as cementing material and in the form of concretions.

Of the minerals not found in all the sands, biotite appears to be the only one of any significance in relation to the origin of the deposits. It is common in sand on the beach, in the old beach deposits beneath the coastal ridge, in the alluvium from Carrum Swamp, and in material from the Main Drain in the Dandenong Swamp. On the other hand, it was not identified in any of the dune sands. This is in agreement with the findings of Retgers (1895), who suggested that, because of its form, biotite is seldom found in wind-blown sands. Its presence in the wind-blown sand forming the tops of the coastal ridges, however, is to be expected in view of the very short distance travelled by the sand from the beach, where biotite was abundant. Even so, the amount of biotite present in the blown sand is noticeably less than on the beach.

In conclusion, the abundance of well-rounded grains of ilmenite, tourmaline and rutile in all the sand deposits suggests that the sand has been derived largely from the pre-existing sedimentary rocks, since for these minerals to become rounded several cycles of erosion are usually necessary (Hatch, Rastall and Black, p. 92). As these minerals are similar to those occurring in the

Tertiary sediments, many of which are unconsolidated, it is probable that much of the sand now forming the inland dunes has been derived from these sediments. Any sand derived from igneous rocks as indicated by the angular condition of the grains, may have come by way of the beach from local granite outcrops near Frankston or from sand carried down from the Eastern Highlands by the rivers.

Physiographic Evolution of Area.

All the sand dunes dealt with are now fixed by vegetation, and there is practically no movement of sand over the area excepting in the coastal ridges. The inland dunes must have been built up, therefore, at some time when there was no protective covering of vegetation, and any sand on the surface was free to be blown about by the wind. To account for these conditions, a much drier climate than that of the present day is necessary.

As has been pointed out above, longitudinal dunes having a north-westerly trend were formed in the Brighton area, and irregular barchan dunes in the Frankston area. As it seems to be generally accepted (Madigan, 1936; Hack, 1941; Bagnold, 1941) that longitudinal dunes are formed parallel to the prevailing wind, it is probable that the Brighton ridges owe their formation to either north-westerly or south-easterly winds. South-easterly winds would probably have brought rain, and it is therefore suggested that strong north-westerly winds blowing from the interior of the continent caused the formation of the longitudinal dunes over the sandy coastal plain.

The reason for the difference in form of the sand ridges in the north-west and south-east parts of the area is probably due to differences in the original topography, and in the sand supply. The origin of various types of dunes has been investigated by Hack (1941), who suggested that longitudinal dunes are developed only over flat areas with a meagre sand supply, whereas barchans require a much greater sand supply for their formation.

A brief investigation of the Tertiary rocks underlying the sand deposits revealed that in the extreme north-west of the area clays and consolidated grits outcrop at the surface; over the Brighton area unconsolidated sands and grits were found only beneath the ridges, and are probably of no great depth. In the central sector, the thickness of the loose sands and grits, judging from the available exposures, is much greater than further north-west. Assuming that the dunes were formed by prevailing north-west winds, the amount of sand available for their information, therefore, was probably much greater towards the south-eastern part of the area than in the extreme north-west.

The coastal plain of the Brighton district is still relatively flat, except for the ridges and, given the required conditions of wind and sand supply, longitudinal dunes would be formed over this area. In the Frankston district, hills of Silurian rock and outcrops of Tertiary grits now project above many of the sand ridges, indicating that the topography of this part of the area was much more irregular than further north-west, and thus longitudinal dune ridges would not be formed in this district.

The drainage system, which developed in the north-western part of the area after the period of dune formation had been brought to a close by a return to moisture conditions, has been determined by the position of the sand ridges rather than by the general slope of the country, which is towards the south-west, and the streams now occupy the valleys which were formed simultaneously with the sand ridges, and therefore trend north-west. The direction of drainage is reversed along the Cheltenham axis, however, and the streams flow south-east towards Carrum Swamp. The presence of this minor divide is due to structures in the underlying Tertiary rocks. Although they are almost horizontal or dip at very slight angles over most of the area, at Beaumaris Bay the beds dip S.E. at 25° and flatten out again on either side, thus forming a monoclinal fold. The low divide, which has been described by Hart (1913) as the "Notting Hill-Cheltenham axis," follows the strike of this fold from Cheltenham to Mitcham. Since there is no abrupt change in the form of the sand ridges crossing the divide, it is probable that inequalities in level of the surface produced by the folding were almost smoothed out by erosion before the formation of the sand ridges.

Another tectonic feature in the underlying rocks which has helped to determine the present physiography is Selwyn's Fault in the south-eastern part of the area. Relative subsidence of the land between the monoclinal fold and Selwyn's Fault has been the chief factor in determining the position of Carrum and Dandenong Swamps, which, however, are of a much later date than the tectonic movements.

The presence of isolated sand hills projecting slightly above the level of the alluvium of the Dandenong Swamp (fig. 2) indicates that this flat area was also covered by sand dunes at one time, but these have probably been eroded to a much greater extent than those to the north-west and south-east, because of the concentration of drainage into this relatively low-lying area. This area probably did not become a swamp until after a general rise of sea level caused the flooding of Port Phillip Bay and brought the coastline approximately to the position of the Wells'-road ridge. It is probable that the coastline was at first rather more irregular and for a very short time was a little further inland than this ridge, which may have been formed first as an off-shore bar and later became the coast as the depression behind it was silted up. As the dune ridge was built up along the former shoreline, drainage from the Dandenong and Eumemmering Creeks was impeded, and the water spread out, forming swamps in which most of the sand from the ridges was removed and redistributed, and the remaining sand hills partially or completely buried. The lunette ridges, situated as they now are along the northern boundary of the alluvial flats, were built up on the northern sides of the swamps, suggesting that the dominant wind causing sand movement was at this time from the south or south-west and not from the north-west as during the dry climatic period.

Recession of the coastline from Wells'-road to its present position, with the consequent formation of a younger dune ridge separating Carrum Swamp from the sea, resulted from a recent emergence of the coastline (Hills, 1940B).

The presence of the depression occupied by Kananook Creek indicates that there are at least two dune ridges very close together. This fact, together with the presence of beach deposits and shell beds $3\frac{1}{2}$ feet above high-tide mark, suggests that there has been a more recent emergence of at least $3\frac{1}{2}$ feet, probably a little more. This is in agreement with further evidence given by Hills (1940B) for a recent emergence of the shores of Port Phillip Bay.

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References.

ANDERSON, G. F., 1926.—Experiments on the Rate of Wear of Sand Grains. *Journ. Geol.*, xxxiv. (2), p.p. 144-158.

BAGNOLD, R. A., 1941.—" The Physics of Blown Sand and Desert Dunes." London, pp. 222-229.

HACK, J. T., 1941.—Dunes of West Navajo Country. *Geog. Rev.*, 31, pp. 240-263.

HART, T. S., 1913.—On the Country Between Melbourne and the Dandenong Creek. *Proc. Roy. Soc. Vic.*, n.s., xxv. (2), pp. 268-285.

HILLS, E. S., 1939.—The Lunette, a New Landform of Aeolian Origin. *Australian Geog.*, 3 (7), p.

————, 1940A.—" The Physiography of Victoria," Melbourne and Sydney. See p. 277.

————, 1940B.—The Question of Recent Emergence of the Shores of Port Phillip Bay. *Proc. Roy. Soc. Vic.*, n.s., lii. (1), pp. 84-105.

HATCH, RASTALL, and BLACK.—" The Petrology of the Sedimentary Rocks." London, p. 92.

JOHNSON, D. W., 1919.—" Shore Processes and Shoreline Development." New York, p. 404.

MADIGAN, C. T., 1936.—The Australian Sand-ridge Deserts. *Geog. Rev.*, xxvi. (2), pp. 205-227.

RETGERS, J., 1895.—Uber die mineralogische and chemische Zuzammensetzung der Dünensand Hollande. *N.J.B.*f.*Min.*, pp. 16-79.

UDDEN, J. A., 1914.—Mechanical Composition of Clastic Sediments. *Bull. Geol. Soc. Am.*, 25, pp. 655-744.